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ESTABLISHING A GPS-BASELINE BETWEEN
SEATTLE, WASHINGTON AND
MONTEREY, CALIFORNIA

by

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December 1989

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A baseline of about 1200 km between Seattle, Washington, and Monterey, California, was measured repeatedly over a six-month period using five-channel, single-frequency Global Positioning System (GPS) receivers with carrier phase differencing techniques and broadcast ephemeris. The averaged GPS baseline length compared favorably with the length determined from control points established by Very Long Baseline Interferometry (VLBI), the agreement being on the order of 0.01 ppm (1 cm in 1200 km) which is about the precision expected of the VLBI technique itself. The quality of the agreement is startling, considering the relatively poorer precision (about 1 ppm) expected for the GPS receivers and techniques employed. To achieve this agreement, GPS observations varying more than 1 ppm from the computed mean length were discarded, and a scale factor of -0.2 ppm for the transformation from GPS to VLBI reference frames was applied, which had been estimated from

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Establishing a GPS-Baseline between Seattle, Washington and Monterey, California

by

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ABSTRACT

A baseline of about 1200 km between Seattle, Washington, and Monterey, California, was measured repeatedly over a six-month period using five-channel, single-frequency Global Positioning System (GPS) receivers with carrier phase differencing techniques and broadcast ephemeris. The averaged GPS baseline length compared favorably with the length determined from control points established by Very Long Baseline Interferometry (VLBI), the agreement being on the order of 0.01 ppm (1 cm in 1200 km) which is about the precision expected of the VLBI technique itself. The quality of the agreement is startling, considering the relatively poorer precision (about 1 ppm) expected for the GPS receivers and techniques employed. To achieve this agreement, GPS observations varying more than 1 ppm from the computed mean length were discarded, and a scale factor of -0.2 ppm for the transformation from GPS to VLBI reference frames was applied, which had been estimated from other studies. The results suggest that accuracies of better than a decimeter are achievable over lines of 1000 km using single-frequency GPS equipment.

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LIST OF ABBREVIATIONS AND ACRONYMS

^{o}C	Celsius degrees
C/A	Coarse/Acquisition Code
cm	centimeter
dms	degrees-minutes-seconds
DoD	Department of Defense
GPS	Global Positioning System
h	hour
in	inch
ION	ionosphere
JD	julian date
^{o}K	Kelvin degrees
km	kilometer
m	meter
mHz	Megahertz
min	minute
μs	microsecond
NAVSTAR	NAVigation Satellite Timing and Ranging
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NPS	Naval Postgraduate School
PDOP	Position Dilution of Precision
PST	Pacific Standard Time
s	second

SEA-TAC	Seattle-Tacoma International Airport
SV	Satellite Vehicle
TEC	Total Electron Content
UTC	Universal Coordinate Time
VLBI	Very Long Baseline Interferometry
WGS84	World Geodetic System 1984
WSO	National Weather Service Office
y	year

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I. INTRODUCTION

The objective of this study is to determine the length of a baseline between Seattle, Washington, and Monterey, California using two independent methods. In one method, independent Global Positioning System (GPS) surveys were used to determine Cartesian coordinates for GPS antennas in Seattle and Monterey. These surveys utilized the National Geodetic Survey (NGS) Very Long Baseline Interferometry (VLBI) stations located near the Seattle and Monterey antenna sites. The second method used GPS only to determine the average position coordinates and slope distance between the two antennas over a six-month period.

GPS presently consists of a seven-satellite constellation in two orbital planes separated in longitude by 120° and inclined at 63° to the equatorial plane. On average, three to six satellites are in view from two to six hours each day, depending on geographical location. All satellites are at an altitude of 20,183 km, resulting in 12-h sideral orbits. A satellite appears in view approximately four minutes earlier each day due to the earth's rotation of almost 361° every 24 hours.

The GPS constellation will be increased to 18 satellites in the 1990's. The full 18-satellite constellation will make it possible to view four or more satellites worldwide

with a minimum of 5^{o} elevation above the horizon (Stein, 1986).

GPS satellites contain cesium and/or rubidium atomic frequency standards accurate to a few parts in 10^{13} per day (Stein, 1986). GPS receivers have an internal quartz oscillator clock. The receiver beats the signal from its clock with the signal from a satellite to produce a beat frequency. This clock comparison is called the carrier beat phase measurement.

The GPS satellites transmit two signals simultaneously, L1 (1575.42 MHz) and L2 (1227.6 MHz). L1 is modulated with a precision (P) code and a coarse acquisition (C/A) code, whereas the L2 signal is modulated with either the P- or C/A-code (Stein, 1986). The P- and C/A-codes are used to identify the GPS satellites and for transit time ranging between the receiver and the satellites (Remondi, 1984). P-code modulation is ten times faster than C/A-code and provides ten times greater precision (Smith, 1987). Presently, P-code is available to all users but will be limited to Department of Defense once the network is fully operational.

Mader and Abell (1985) found baseline lengths to be repeatable to within an average of 0.24 ppm for distances of 300 to 1600 km for two-day periods, and repeatabilities of about 2 ppm have been measured over 300- to 500-km baselines over five-day periods (Lachapelle and Cannon, 1986).

II. METHODS

A. DIFFERENCING THE CARRIER PHASE

Correlations may be made among signals received at stations simultaneously tracking the same satellites. Errors in such signals may also be correlated. Because of these correlations the accuracy of relative positions may be improved by taking the differences between measurements to remove or greatly reduce errors.

1. Single Difference

Single differencing (Figure 1) eliminates receiver clock errors. A single difference is formed by differencing carrier phases at the same epoch. A single difference can be expressed as (Ashkenazi et al., 1985):

$$N_{ABj}(\tau) = \alpha_{ABj} + (f_B - f_A)(\tau - \tau_o) + \frac{f_j}{c}[R_{Bj}(\tau) - R_{Aj}(\tau)] + N^{AB}_{ion} + N^{AB}_{trop} \qquad (1)$$

where

$$\alpha_{ABj} = [N_B(\tau_o) - N_A(\tau_o)] - [N^B_j(\tau_o) - N^A_j(\tau_o)] \qquad (2)$$

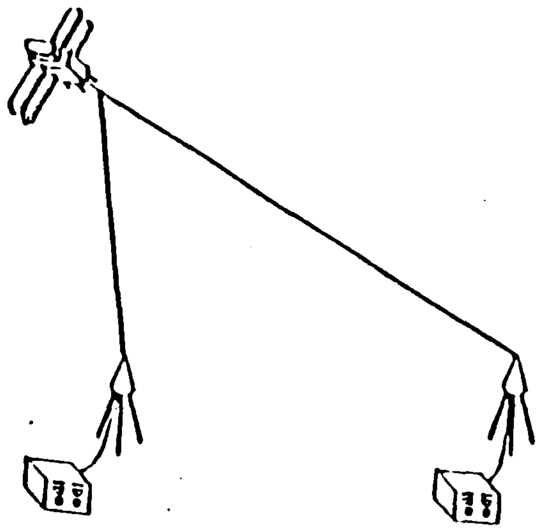

Figure 1. Single Differencing with One Satellite (Wells et al., 1986)

and

α_{ABj}	:	initial (at time τ_o) clock bias;
$N_{ABj}(\tau)$	:	difference at local epoch τ of the GPS carrier phase readings at stations A and B;
$f_B - f_A$	:	frequency offset between the receivers at stations A and B;
f_j	:	satellite oscillator frequency;
τ_o, τ	:	initial lock-on time, observation time;
c	:	velocity of microwave propagation in vacuum;
R_{Aj}, R_{Bj}	:	the range between stations A,B to satellite j;
N_{ion}	:	ionospheric delay;
N_{trop}	:	tropospheric delay.

2. <u>Double Difference</u>

To eliminate both local and satellite clock errors, double differences (Figure 2) are formed by differencing the single differences between two satellites at the same epoch. The double difference can be written:

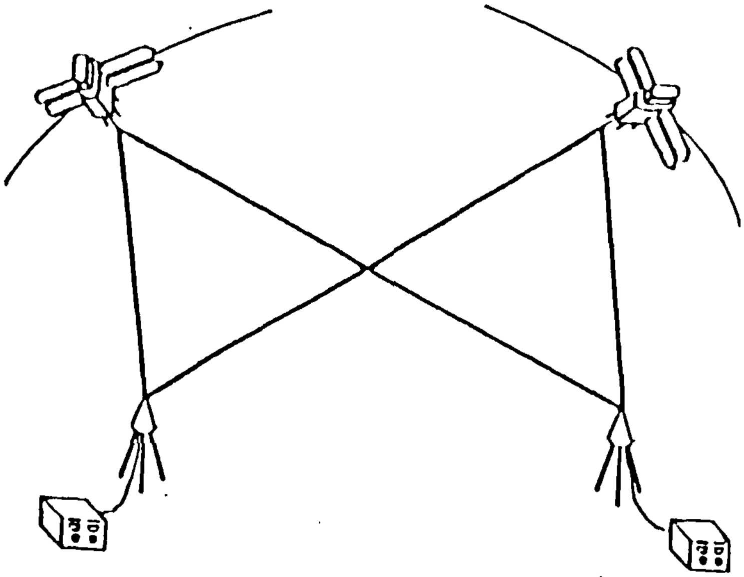

Figure 2. Double Differencing with Two Satellites (Wells et al., 1986)

$$N_{ABjk}(\tau) = \alpha_{ABjk} + N_{ion}^{ABjk} + N_{trop}^{ABjk} + \frac{f_j}{c}[R_{Bk}(\tau) - R_{Ak}(\tau) - R_{Bj}(\tau) + R_{Aj}(\tau)] \quad (3)$$

where

$$N_{ABjk}(\tau) = N_{ABk}(\tau) - N_{ABj}(\tau) \quad (4)$$

and

$$\alpha_{ABjk}(\tau) = \alpha_{ABk}(\tau) - \alpha_{ABj}(\tau) \quad (5)$$

3. <u>Triple Difference</u>

Triple differencing (Figure 3) eliminates all errors found in double differencing as well as cycle slips. The triple difference can be written:

$$N_{ABjk}(\tau_1,\tau_2) = N_{ABjk}(\tau_2) - N_{ABjk}(\tau_1) \quad (6)$$

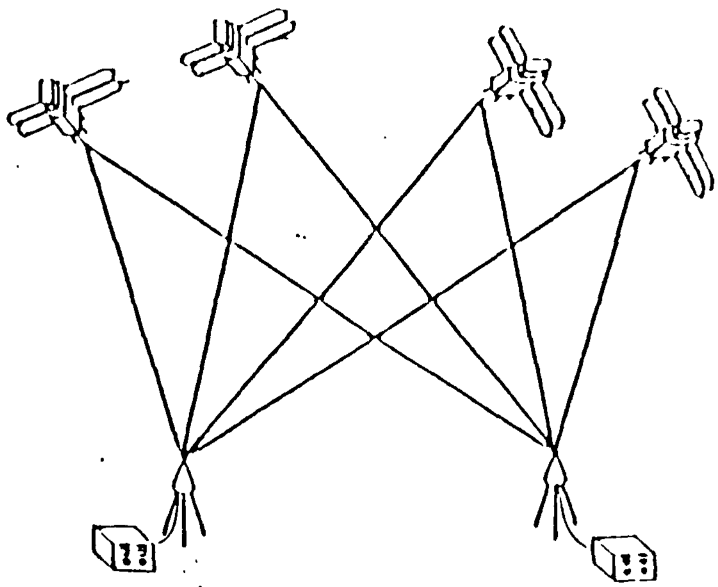

Figure 3. Triple Differencing with Four Satellites (Wells et al., 1986)

B. ERRORS IN SINGLE-FREQUENCY DATA

The sum of all biases adding to or subtracting from a satellite's projected range is called the range bias. Common biases found in single-frequency observations are

related to satellite clock, receiver clock, orbital, ionospheric and tropospheric delays, and the carrier beat phase.

Satellite clock biases may lead to 10-m range errors if broadcasted corrections are used, while receiver clock biases may lead to 10- to 100-m errors, depending on the type of receiver oscillator (Wells et al., 1986). As explained above, these errors can be removed by differencing the data.

Orbital biases result from the departure of a satellite from its broadcasted ephemeris or predicted orbit. Orbital biases propagate into a computed baseline when the GPS orbit coordinates are fixed in processing (Hothem and Williams, 1985), and can lead to errors of up to 80 m for broadcasted ephemerides (Wells et al., 1986).

The GPS signal is affected by nonlinear dispersion in the atmosphere which can lead to range biases of more than 150 m at a sunspot maximum to less than 5 m at a sunspot minimum (Wells et al., 1986). Group velocities at radio frequencies are retarded by the ionosphere by an amount proportional to the total electron content (TEC) along the signal's path and inversely proportional to the square of the frequency (Goad, 1985). The TEC is a function of the time of day and year, latitude, longitude, and sunspot activity (Stoichar, 1985). Ionospheric errors increase towards the equator where sunlight is more intense. Dual-frequency receivers can be used to measure the ionospheric

delay by comparing delays at the two frequencies (Kaniuth, 1986). For single-frequency receivers ionospheric delay must be estimated on the basis of TEC predictions (Smith, 1987).

Tropospheric biases are proportional to the refractivity found in the non-ionized atmosphere along the satellite-receiver path. Radio waves in the stratosphere and troposphere are not dispersive up to 30 GHz (Kaniuth, 1986). Refractivity can be written as $N = (n-1) \times 10^6$ where n is the refractive index. Tropospheric biases vary from approximately 2.3 m at the zenith to 20 m at 10^o above the horizon.

Carrier beat phase biases can result in gross errors. A 1-μs miss-synchronization between the satellite and receiver clocks creates a 300-m range bias (Wells et al., 1986).

Position Dilution of Precision (PDOP) is a component of Geometric Dilution of Precision (GDOP), which is a measure of how satellite geometry degrades accuracy (Jorgenson, 1984). The Trimble 4000SX receiver used for our observations records PDOP every five minutes. PDOP is related to GDOP by:

$$GDOP^2 = PDOP^2 + TDOP^2 \qquad (7)$$

where TDOP is Time Dilution of Precision (Jorgenson, 1984). TDOP is the error in the user clock bias multiplied by the

propagation speed. PDOP peaks occur when the satellites lie in a common plane.

GPS observations should be made close to 2400 local time once 24-h satellite visibility is available. This, in conjunction with low PDOPs, should minimize ionospheric and tropospheric errors.

III. SITE SURVEYS AND INSTRUMENTS

A. SEATTLE, WASHINGTON

The first factors to determine in establishing the baseline were the positions of the antennas in Seattle and Monterey. This was done by using Trimble 4000SX GPS receivers. One receiver was installed and tested on 25 September 1987 at NOAA's Sand Point Facility in Seattle, Washington (Figures 5 and 6). A second Trimble 4000GPS receiver was used to locate the Sand Point antenna with respect to a nearby VLBI control point (referred to as AVIATION 2). This VLBI antenna position and another near the Monterey GPS antenna site were used to check the GPS-determined baseline between Seattle and Monterey (Figure 4). Satellites 6, 9, 11, 12, and 13 were used during our observations.

The GPS antenna position at Seattle was determined using one 90-min GPS observation session with a double difference carrier phase solution (Table 1). This solution determines the change in coordinates between the two antennas. Let Δ be the difference between the corresponding coordinates for the antennas at stations Aviation 2 and Seattle and σ_{Δ} its standard deviation. The standard deviation of Seattle, σ_S, is:

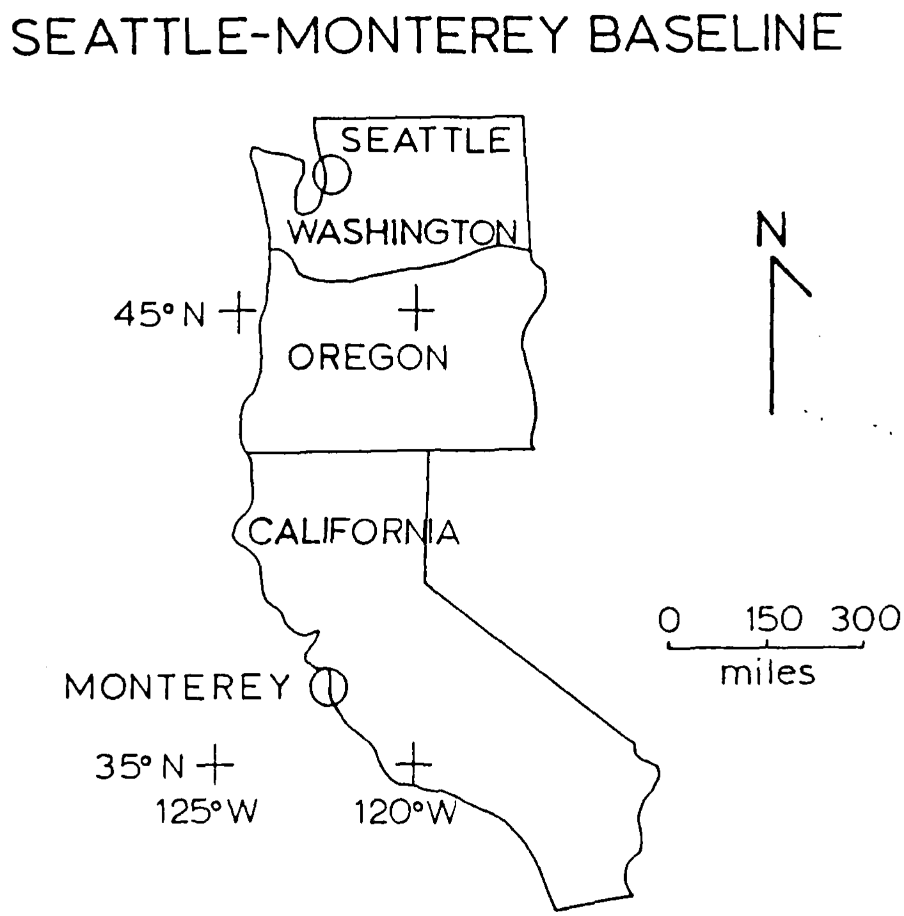

Figure 4. Station Location Map Showing Monterey, California, and Seattle, Washington

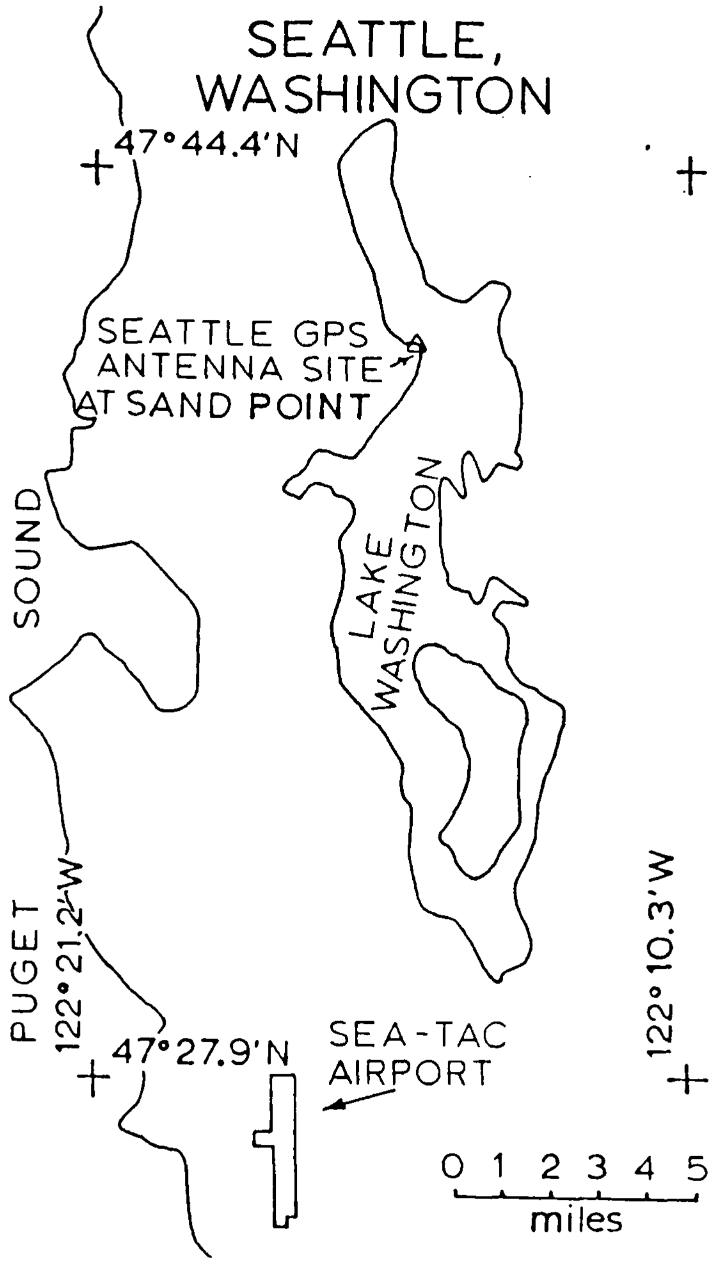

Figure 5. The Environs of Seattle, Washington, Showing the Location of Sand Point and the Seattle-Tacoma Airport

$$\sigma_S = (\sigma_A^2 + \sigma_\Delta^2)^{1/2} \tag{8}$$

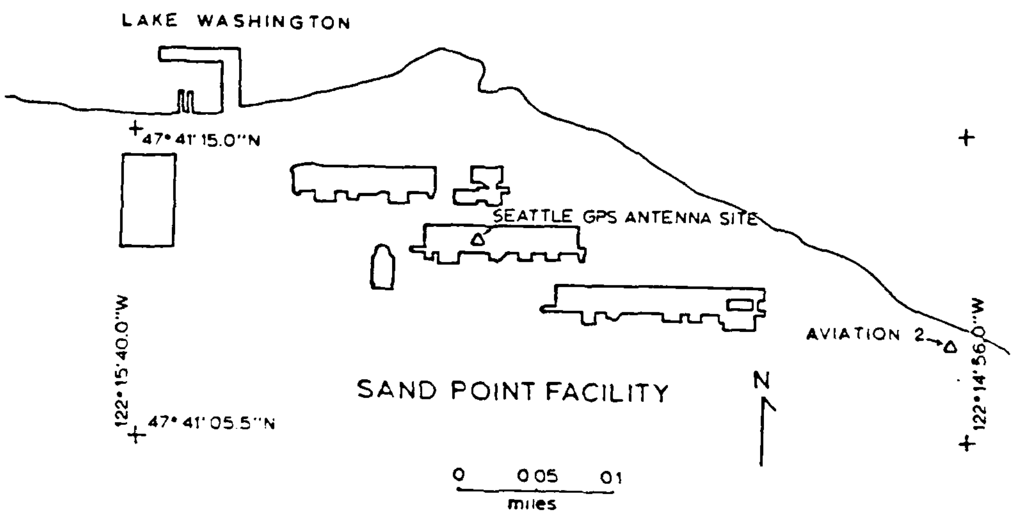

Figure 6. Location of Seattle GPS Antenna Relative to the VLBI Control Point

TABLE 1

RESULTS OF ANTENNA LOCATION SURVEY IN SEATTLE (Bouchard, 1988)

	Aviation 2 Coordinate	σ_A	Seattle Coordinate	σ_S	Δ	σ_Δ
X	-2295347.760	0.017	-2295756.121	0.017	-408.361	0.002
Y	-3638029.429	0.028	-3637699.228	0.028	330.200	0.002
Z	4693408.964	0.032	4693482.777	0.032	73.813	0.003

Receiver clock, satellite clock, and orbital errors are likely responsible for the standard deviations in Table 1.

B. MONTEREY, CALIFORNIA

The GPS station position at Monterey (Figure 7) was found by differential GPS using FT ORD NCMN 1981, a VLBI

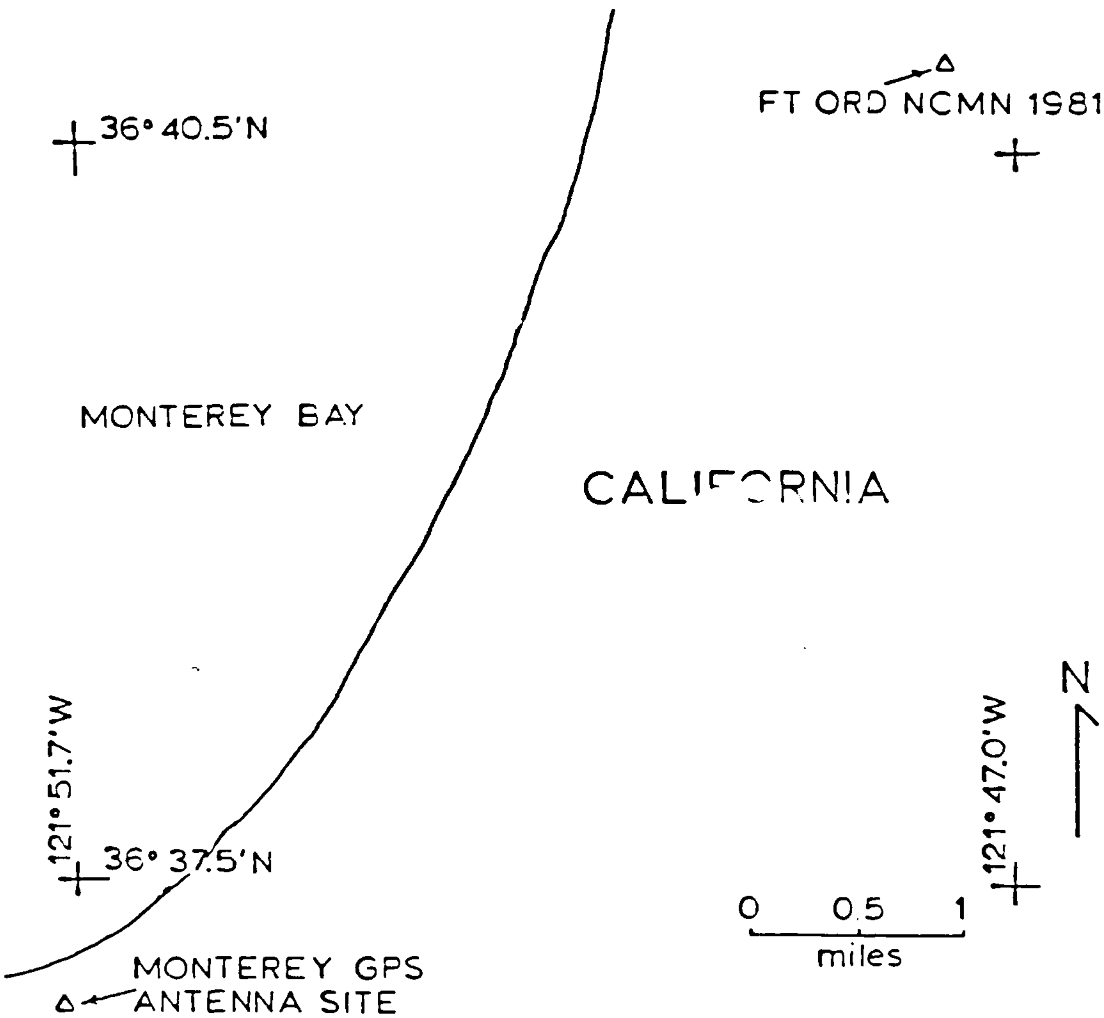

Figure 7. Location of Monterey GPS Antenna Relative to the VLBI Control Point

control point, as the primary station. Data collected during two observing sessions were averaged to give antenna positions. The first observing session was 112 min in length while the second was 126 min. The Cartesian coordinates of each GPS antenna used in the observing sessions were included in the post-processed output. These values are listed in Table 2 under the columns FT ORD and Monterey. Δ and σ_{Δ} were computed as described in Section A above.

TABLE 2

RESULTS OF ANTENNA LOCATION SURVEYS IN MONTEREY

SURVEY DATE: 09/16/87

	FT ORD	σ_O	Monterey	σ_M	Δ	σ_{Δ}
X	-2697026.493	0.007	-2707340.093	0.032	-10313.601	0.032
Y	-4354393.309	0.010	-4353475.617	0.049	917.693	0.048
Z	3788077.778	0.009	3781740.387	0.042	-6337.391	0.041

SURVEY DATE: 09/18/87

	FT ORD	σ_O	Monterey	σ_M	Δ	σ_{Δ}
X	-2697026.493	0.007	-2707340.095	0.037	-10313.602	0.037
Y	-4354393.309	0.010	-4353475.620	0.050	917.689	0.049
Z	3788077.778	0.009	3781740.389	0.045	-6337.389	0.044

AVERAGE MONTEREY ANTENNA POSITION:

	Monterey	σ_M
X	-2707340.094	0.034
Y	-4353475.618	0.050
Z	3781740.388	0.044

IV. DATA ACQUISITION

A. GPS

GPS positioning data acquired throughout the experiment were collected using at least four of the five satellites available (6, 9, 11, 12, and 13). This set was chosen because the satellites were well positioned for viewing from both Seattle and Monterey (Figure 8). Five satellites allowed observation periods of at least 100 min. For an additional 80 min four satellites were still visible.

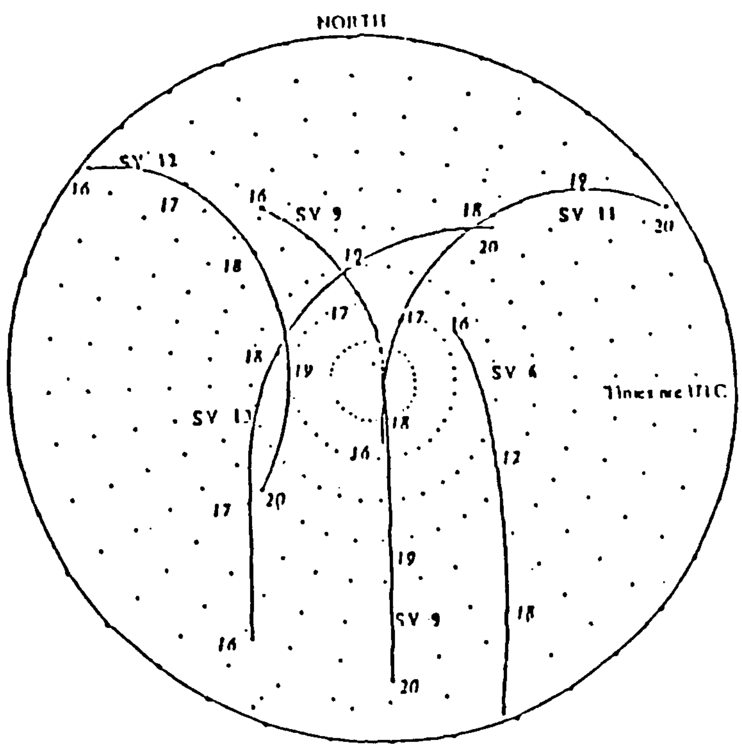

Figure 8. Satellite Tracks Relative to Monterey. The Zenith for Monterey is at the Center, While the Horizon is on the Outer Perimeter

GPS data were collected from 29 September 1987 until 31 March 1988 with Trimble 4000SX single-frequency (C/A-code), five-channel receivers. The receivers log all carrier phase data via Grid laptop microcomputers onto 3.5-in floppy disks (Trimble Navigation, 1987).

Observations were made Tuesdays through Saturdays except on days after Federal holidays. Reasons for not processing certain days included bad satellite health, power failures, or the unavailability of meteorological data.

The 4000SX receiver uses the C/A code to decode the GPS navigation message so it can automatically track satellites. It also acts in a time transfer mode to determine offset and drift of its own clock, thus providing accurate time tags for observations without external atomic clocks or synchronization with the receiver at the other end of the baseline. The receivers were left on continuously throughout the six-month period to allow unattended data acquisition. They were controlled using Trimble's Version D "Datalogger" acquisition software. The station reference position, antenna height, and any additional information were entered into the receiver via its keypad.

Each day the desired satellites and their minimum acceptable elevations were set from the computer. A minimum elevation of 15 degrees above the horizon was used to control when the receivers would start collecting satellite data. This 15-degree elevation is based on when minimum

error biases due to both the ionized and non-ionized parts of the atmosphere start to occur.

Receiver clock parameters were logged to the floppy disk every 15 s and antenna positions every 5 min. The GPS navigation message, ionospheric and Universal Coordinated Time (ION/UTC) data, and an optional user message were transferred to separate files at the beginning of each session. The ION/UTC data contain ionospheric parameters for dual frequency receivers and UTC time parameters to initialize the receiver's clock.

B. METEOROLOGICAL

Meteorological parameters for tropospheric corrections were obtained daily from the NPS Department of Meteorology. Values for Seattle were recorded by the Weather Service Office of the Seattle-Tacoma International Airport (SEA-TAC) approximately 27 km from the Seattle site (Figure 5). Values used for Monterey were measured hourly by the NPS Department of Meteorology approximately 300 m south of the antenna site.

V. DATA ANALYSIS

A. COORDINATE SYSTEM

All GPS data were processed using the World Geodetic System 1984 (WGS 84) coordinate system, based upon broadcast ephemeris of the GPS satellites. However, a small but systematic difference between GPS- and VLBI-derived WGS 84 coordinates turned out to be significant. The broadcast GPS ephemeris, which predicts positions of the satellites in WGS 84 coordinates, affected the baseline distances determined by the carrier phase differential technique. On the other hand, VLBI control points, originally in the VLBI reference frame, were used to derive WGS 84 coordinates for the GPS antenna positions in Seattle and Monterey, and hence affected the baseline distance estimated by differencing these positions.

The possibility of systematic differences between the GPS- and VLBI-derived WGS 84 positions has been investigated by Abusali et al. (1989). In their study, a set of positions expressed in the two coordinate systems (VLBI and GPS/WGS-84) were compared to empirically determine a best-fitting transformation between them. A conventional seven-parameter transformation model was used: three translations and three rotations of the XYZ axes plus a scale factor for any proportional differences in length. The specific set of

positions used happened to be those of the GPS satellites determined by simultaneous tracking from two sets of ground stations, one with coordinates given in the GPS system and the other given in VLBI-derived coordinates.

Their results suggested that a scale factor on the order of -0.1 to -0.2 ppm may exist (in the sense of transforming from distances in the GPS system to those in the VLBI system). However, these results were not applicable directly to the question here; that is, what if any systematic scale factor exists between the broadcast GPS ephemeris and VLBI systems? The broadcast ephemeris includes an orbit prediction model which was not considered in the Abusali study. In a private communication, Abusali (1989a) indicated a scale factor of about -0.2 ppm (GPS to VLBI) should be expected if using broadcast ephemeris.

This estimate of the scale factor was applied in the comparison between GPS- and VLBI-determined slope distances as discussed in Section VI, Results. Otherwise, it was not applied to the data analysis described here.

B. GPS-BASELINE DETERMINATION

1. Six-month Averaged Baseline Length

Observations collected during each GPS session were divided into 10-min segments using INTER_H.BAS (Appendix A) to observe the effect of varying satellite geometry on the baseline. GETHDAT.BAS (Appendix B) was used to read and store all slope distances processed by Trimble's TRIM640.EXE

(Revision AB). Outlying values of slope distance were removed by eliminating those exceeding a 3σ value. 3σ represents 99% of those accepted slope distances surrounding the mean. The 3σ value was computed by:

$$3\left[\frac{\Sigma V_i^2}{n-1}\right]^{1/2} \qquad (9)$$

where:

$V_i = \mu - X_i$;

μ = mean value of slope distance;

X_i = observed value of slope distance based on 10-min averages;

n = total number of values.

Once the value of σ is known, it can be found in parts per million (ppm) as:

$$(\sigma/L)10^6 \qquad (10)$$

where:

L = the mean slope distance.

The rejection criterion above was repeated using those values within 3σ if the value of σ was more than 1 ppm. This value was chosen because it was well within the standards for first order surveys of baselines of this length. (For additional comments see Bouchard (1988 , p.

50).) Four iterations were required to achieve an accuracy better than 1 ppm. The standard deviation around the mean was then computed by:

$$\sigma_m = \sigma/(n)^{1/2} \tag{11}$$

Using σ_m in place of σ in Equation (10), σ_m may be expressed in ppm. The final computed slope distance is 1230045.532 ± 0.025 m (0.02 ppm).

This value is well within the allowable limit for first order surveys (1:100,000) of the National Geodetic Reference System (Terrestrial).

2. Ninety-Four-Day Baseline Length

GPS data from 94 days were processed using triple differencing. These data were not divided as in Section I but rather processed at one time to ensure that the PDOP passed through infinity. It is with this rapidly changing PDOP that best results are acquired (Trimble Navigation, 1987; Bouchard, 1988). The average X, Y, and Z values are noted in Table 3. The slope distance was computed using:

$$D = (\Delta X^2 + \Delta Y^2 + \Delta Z^2)^{1/2} \tag{12}$$

TABLE 3

CARTESIAN COORDINATES OF GPS DETERMINED ANTENNA POSITIONS

	Seattle	Monterey
X	-2295759.503 ± 1.277	-2707343.469 ± 1.341
Y	-3637704.115 ± 0.971	-4353480.402 ± 0.945
Z	4693484.159 ± 0.729	3781742.430 ± 0.731

The standard error in the slope distance was then computed as:

$$\sigma_D = \{[(\Delta X\ \sigma_{\Delta X})/D]^2 + [(\Delta Y\ \sigma_{\Delta Y})/D]^2 \quad [(\Delta Z\ \sigma_{\Delta Z})/D]^2\}^{1/2} \tag{13}$$

where D is the slope distance. $\sigma_{\Delta X}$, $\sigma_{\Delta Y}$, and $\sigma_{\Delta Z}$ were computed using:

$$\sigma_\Delta = \pm(\sigma_1{}^2 + \sigma_2{}^2)^{1/2} \tag{14}$$

where σ_1 and σ_2 are the standard errors of Seattle and Monterey.

The final computed slope distance was 1230044.750 ± 1.261 m. It is suspected that the high PDOP values included in the data processing contributed to a higher standard deviation for D when compared to the slope distance in Section I.

3. VLBI-Determined Antenna Position

The VLBI positions were obtained in NAD83 Cartesian coordinates from the Gravity, Astronomy and Space Geodesy Branch of the National Geodetic Survey (NGS). The Defense Mapping Agency Hydrographic/Topographic Office validated the direct transformation of the VLBI Cartesian coordinates to WGS84 Cartesian coordinates (Kumar, 1988).

The Monterey-Seattle VLBI antenna positions given in Tables 1 and 2 were used to check the baselines computed in Sections I and II. The Cartesian coordinates of the VLBI-determined antenna positions were computed using double difference processing. This processing technique was chosen because the root-mean-square (RMS) of fit was less than 0.05 cycles, which is common for baselines less than 30 km (Trimble Navigation, 1987). The method used to compute the Monterey-Seattle baseline and its standard deviation is discussed in Section II. Computed values are in Table 4.

TABLE 4

VLBI/GPS POSITIONED ANTENNA BASELINE DISTANCES

ΔX	-411583.973 $\pm$	0.040
ΔY	-715776.390 $\pm$	0.058
ΔZ	-911742.338 $\pm$	0.054
Slope Distance:	1230045.280	0.054

This slope distance yields 0.04 ppm. Precisions of 0.01 ppm have been achieved with VLBI and 1 ppm with GPS over 1600-km baselines in Alaska and Canada (Mader and Abell, 1985).

VI. RESULTS AND CONCLUSIONS

The six-month averaged GPS slope distance differs significantly from that determined by the VLBI-derived antenna positions, the GPS distance being about 25 cm too long.

	Slope Distance (meters)	Estimated Standard Deviation
VLBI	1230045.280	0.054
GPS	1230045.532	0.025
Difference	-0.252	

Given the estimated precisions on each distance, this difference suggests that some systematic effects remain. (The hypothesis of equal distances can be rejected at about the 98% confidence level in favor of the GPS value being greater by using a Fischer-Barents test for samples with unequal variances.)

As discussed in Section IV.A, studies at the Center for Space Research, University of Texas (Abusali, et al., 1989), suggest that a systematic scale error exists between the GPS- and VLBI-derived coordinate systems. Adopting their best estimate of -0.2 ppm for the scale error between GPS broadcast ephemeris and VLBI coordinates (Abusali, 1989), brings these measurements into close agreement:

GPS length	=	1230045.532 m	
-0.2 ppm	=	-0.246 m	
		1230045.286 m	Transformed GPS distance

which differs by about 1 cm from the VLBI-derived distance (with an estimated precision of about 6 cm, one standard deviation).

This result indicates that accuracies of better than 10 centimeters can be achieved with single-frequency GPS equipment over relatively long baselines, on the order of 1000 km. Careful averaging of repeated measurements is essential in order to reduce the incompletely modelled effects of ionospheric and tropospheric paths differences over such long lines. And although this result was achieved using broadcast ephemeris, precise ephemeris should be used whenever possible in order to eliminate systematic errors due to orbit predictions methods employed by GPS.

This result also tends to confirm the existence of a systematic scale error between the GPS and VLBI coordinate systems. This scale error, however, is significant only to those users mixing VLBI- and GPS-derived information. Most will work entirely within the WGS 84 coordinate system using only GPS-derived positions.

APPENDIX A

PROGRAM INTER H.BAS LISTING

```
1 REM THIS PROGRAM CREATES A BATCH FILE TO BE USED WITH
TRIMBLES POSTPROCESSING SOFTWARE "TRIMVEC."  IT DOES A
LINEAR INTERPOLATION OF METEOROLOGICAL VALUES FOR A
GIVEN DAY FOUND IN THE "MET.DAT" FILE.  THIS PROGRAM
COMPUTES FOR EVERY 10 MINUTES.
10 INPUT "BATCH FILE NAME?";A$
20 OPEN "DEPOSIT.H" FOR APPEND AS #1
30 OPEN "MET.DAT" FOR INPUT AS #2
40 INPUT "MONTH?";M$
50 INPUT "DAY?";D$
60 INPUT "JULIAN DAY?";JD
62 DIM A$(18)
63 A$(2)=" h02.":A$(3)=" h03.":A$(4)=" h04.":A$(5)="
    h05.":A$(6)=" h06.":A$(7)=" h07.":A$(8)="
    h08.":A$(9)="
    h09.":A$(10)=" h10.":A$(11)=" h11.":A$(12)="
    h12.":A$(13)="
    h13.":A$(14)=" h14.":A$(15)=" h15.":A$(16)="
    h16.":A$(17)="
    h17.":A$(18)=" h18."
65 JD$=STR$(JD)
67 W$=" "
70 C$="command /c tbf h.tem ":F$="sa"+JD$+"
ma"+JD$:S$=C$+F$
80 INPUT "START HOUR?";SH
90 INPUT "START MINUTE?";SM
100 INPUT #2,ID1,IH1,P1,T1,R1,P2,T2,R2
110 IF (ID1<>JD) THEN 100
120 IF (SH<>IH1) THEN 100
130 P1=P1-2:T2=(T2-32)*5/9
140 INPUT #2,ID2,IH2,P3,T3,R3,P4,T4,R4
150 P3=P3-2:T4=(T4-32)*5/9
160 IF ID1<>ID2 THEN 260
165 REM THIS NEXT SECTION COMPUTES FRACTIONAL VALUES
    FOR FUTURE LINEAR INTERPOLATION.
170 FOR I=1 TO 6
180 A=A+IH1:B=B+P1:C=C+T1:D=D+R1:E=E+P2:F=F+T2:G=G+R2
190 PRINT #1,ID1,A,B,C,D,E,F,G
200 PRINT ID1,A,B,C,D,E,F,G
210 IF I>1 GOTO 230
220
IH1=(IH2-IH1)/6:P1=(P3-P1)/6:T1=(T3-T1)/6:R1=(R3-R1)/6:
    P2=(P4-P2)/6:T2=(T4-T2)/6:R2=(R4-R2)/6
230 NEXT I
```

```
240 ID1=ID2:IH1=IH2:P1=P3:T1=T3:R1=R3:P2=P4:T2=T4:R2=R4
245 A=0:B=0:C=0:D=0:E=0:F=0:G=0
250 GOTO 140
260 CLOSE #1
270 CLOSE #2
280 OPEN A$ FOR APPEND AS #1
290 OPEN "DEPOSIT.H" FOR INPUT AS #2
300 INPUT #2,ID1,IH1,P1,T1,R1,P2,T2,R2
310 IF (ID1<>JD) THEN 300
320 IF (SH<>INT(IH1)) THEN 300
325 REM FRACTIONAL MINUTE IS NOW COMPUTED AND TESTED
    WITH THE FRACTIONAL HOUR.
330 FM=SM/60
340 IF (SH+FM-.0833)>IH1 OR (SH+FM+.0833)<IH1 THEN 300
344 IH=INT(IH1):IM=(IH1-IH)*60
346 IF IM-INT(IM)>.5 THEN IM=IM+(1-(IM-INT(IM)))
348 IF IM-INT(IM)<.5 THEN IM=INT(IM)
350 IM2=IM+10:IH2=IH
351 REM THIS NEXT SECTION IS A ROUNDING OFF ROUTINE.
352 IF IM2>60 THEN IH2=IH+1 AND IM2=IM2-60
354 IF P1=INT(P1) THEN 356
355 P1=INT(P1)+((INT((P1-INT(P1))*10))/10)
356 IF T1=INT(T1) THEN 358
357 T1=INT(T1)+((INT((T1-INT(T1))*10))/10)
358 R1=INT(R1)
359 IF P2=INT(P2) THEN 361
360 P2=INT(P2)+((INT((P2-INT(P2))*10))/10)
361 IF T2=INT(T2) THEN 363
362 T2=INT(T2)+((INT((T2-INT(T2))*10))/10)
363 R2=INT(R2)
370
P1$=STR$(P1):T1$=STR$(T1):R1$=STR$(R1):P2$=STR$(P2):
    T2$=STR$(T2):R2$=STR$(R2):P$="h01.":IM$=STR$(IM):I-
    H$=STR$(I-
    H):IM2$=STR$(IM2):IH2$=STR$(IH2)
380 PRINT
    #1,S$+P$+JD$+P1$+T1$+R1$+P2$+T2$+R2$+W$+M$+W$+D$+-
    IH$+IM$+IH2$+IM2$
390 PRINT
    S$+P$+JD$+P1$+T1$+R1$+P2$+T2$+R2$+W$+M$+W$+D$+
    IH$+IM$+IH2$+IM2$
400 IM=IM2:IH=IH2
410 FOR N=2 TO 18
420 INPUT #2,ID1,IH1,P1,T1,R1,P2,T2,R2
423 IH=INT(IH1):IM=(IH1-IH)*60
424 IF IM-INT(IM)>.5 THEN IM=IM+(1-(IM-INT(IM)))
425 IF IM-INT(IM)<.5 THEN IM=INT(IM)
426 IM2=IM+10:IH2=IH
427 REM THIS NEXT SECTION IS A ROUNDING OFF ROUTINE.
429 IF IM2>60 THEN IH2=IH+1 AND IM2=IM2-60
430 IF P1=INT(P1) THEN 432
431 P1=INT(P1)+((INT((P1-INT(P1))*10))/10)
```

```
432 IF T1=INT(T1) THEN 434
433 T1=INT(T1)+((INT((T1-INT(T1))*10))/10)
434 R1=INT(R1)
435 IF P2=INT(P2) THEN 437
436 P2=INT(P2)+((INT((P2-INT(P2))*10))/10)
437 IF T2=INT(T2) THEN 439
438 T2=INT(T2)+((INT((T2-INT(T2))*10))/10)
439 R2=INT(R2)
447
P1$=STR$(P1):T1$=STR$(T1):R1$=STR$(R1):P2$=STR$(P2):
    T2$=STR$(T2):R2$=STR$(R2):IM$=STR$(IM):IH$=STR$(IH-
    ):IM2$=ST-R$(IM2):IH2$=STR$(IH2)
450 PRINT
    #1,S$+A$(N)+JD$+P1$+T1$+R1$+P2$+T2$+R2$+W$+M$+
    W$+D$+IH$+IM$+IH2$+IM2$
460 PRINT S$+A$(N)+JD$+P1$+T1$+R1$+P2$+T2$+R2$+W$+M$+
    W$+D$+IH$+IM$+IH2$+IM2$
470 IM=IM2:IH=IH2
480 NEXT N
490 END
```

APPENDIX B

PROGRAM GETHDAT.BAS LISTING

```
1 REM THIS PROGRAM WITHDRAWS THE SLOPE DISTANCE, X, Y,
    AND Z, OF TRIMVEC'S ASCII PRINTOUT.
4 DATA 272,273,274,275,276,279,280,281,282,287
5 FOR K = 1 TO 46
7 A = 20
10 READ JD$
20 OPEN "H01."+JD$ FOR INPUT AS #1:GOTO 110
25 OPEN "H02."+JD$ FOR INPUT AS #1:GOTO 110
30 OPEN "H03."+JD$ FOR INPUT AS #1:GOTO 110
35 OPEN "H04."+JD$ FOR INPUT AS #1:GOTO 110
40 OPEN "H05."+JD$ FOR INPUT AS #1:GOTO 110
45 OPEN "H06."+JD$ FOR INPUT AS #1:GOTO 110
50 OPEN "H07."+JD$ FOR INPUT AS #1:GOTO 110
55 OPEN "H08."+JD$ FOR INPUT AS #1:GOTO 110
60 OPEN "H09."+JD$ FOR INPUT AS #1:GOTO 110
65 OPEN "H10."+JD$ FOR INPUT AS #1:GOTO 110
70 OPEN "H11."+JD$ FOR INPUT AS #1:GOTO 110
75 OPEN "H12."+JD$ FOR INPUT AS #1:GOTO 110
80 OPEN "H13."+JD$ FOR INPUT AS #1:GOTO 110
85 OPEN "H14."+JD$ FOR INPUT AS #1:GOTO 110
90 OPEN "H15."+JD$ FOR INPUT AS #1:GOTO 110
95 OPEN "H16."+JD$ FOR INPUT AS #1:GOTO 110
100 OPEN "H17."+JD$ FOR INPUT AS #1:GOTO 110
105 OPEN "H18."+JD$ FOR INPUT AS #1:GOTO 110
110 A=A+5
115 OPEN "GETHDAT.PRN" FOR APPEND AS #2
120 FOR CA = 1 TO 14
122 INPUT #1, A$
124 NEXT CA
126 INPUT #1, A$
128 W$=MID$(A$,12,10)
129 IF A >= 95 GOTO 144
130 FOR CA = 1 TO 78
132 INPUT #1, A$
140 NEXT CA
142 GOTO 150
144 FOR CA = 1 TO 74
146 INPUT #1, A$
148 NEXT CA
150 FOR CJ = 1 TO 4
160 INPUT #1, A$
170 IF CJ = 2 GOTO 200
180 IF CJ = 3 GOTO 210
185 IF CJ = 4 GOTO 215
```

```
190 AA$ = MID$(A$,11,12)
200 B$ = MID$(A$,11,12)
210 C$ = MID$(A$,11,12)
215 H$ = MID$(A$,18,8)
220 NEXT CJ
240 INPUT #1, A$
260 INPUT #1, A$
270 G$ = MID$(A$,24,12)
272 PRINT W$, G$, C$, H$
280 PRINT #2, W$, G$, C$, H$
300 CLOSE #2
310 CLOSE #1
320 IF A = 25 GOTO 25
330 IF A = 30 GOTO 30
335 IF A = 35 GOTO 35
340 IF A = 40 GOTO 40
345 IF A = 45 GOTO 45
350 IF A = 50 GCTO 50
355 IF A = 55 GOTO 55
360 IF A = 60 GOTO 60
365 IF A = 65 GOTO 65
370 IF A = 70 GOTO 70
375 IF A = 75 GOTO 75
380 IF A = 80 GOTO 80
385 IF A = 85 GOTO 85
390 IF A = 90 GOTO 90
395 IF A = 95 GOTO 95
400 IF A = 100 GOTO 100
405 IF A = 105 GOTO 105
410 NEXT K
415 END
```

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